

Liquefaction Potential Index: Field Assessment

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Abstract: Cone penetration test (CPT) soundings at historic liquefaction sites in California were used to evaluate the predictive capability of the liquefaction potential index (LPI), which was defined by Iwasaki et al. in 1978. LPI combines depth, thickness, and factor of safety of liquefiable material inferred from a CPT sounding into a single parameter. LPI data from the Monterey Bay region indicate that the probability of surface manifestations of liquefaction is 58 and 93%, respectively, when LPI equals or exceeds 5 and 15. LPI values also generally correlate with surface effects of liquefaction: Decreasing from a median of 12 for soundings in lateral spreads to 0 for soundings where no surface effects were reported. The index is particularly promising for probabilistic liquefaction hazard mapping where it may be a useful parameter for characterizing the liquefaction potential of geologic units.

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Introduction

Liquefaction hazard maps increasingly are being incorporated into earthquake hazard mitigation practice. Initially, most maps resulted from research efforts by geotechnical engineers and geologists and their use by communities was voluntary (Power and Holzer 1996). However, as the methodology matured, maps have become incorporated in the seismic safety plans of communities, and most recently have been adopted in California for regulatory purposes (CDMG 1997). Because liquefaction hazard maps typically portray the hazard of large areas, their efficient production requires that they be based on surficial geologic maps. A significant challenge in the conversion of geologic maps to hazard maps has been the assessment of the degree of hazard posed by each geologic unit. Typically qualitative rankings are used (e.g., Youd and Hoose 1977), although the scales commonly are based to some extent on penetration testing in individual units. These rankings typically attempt to characterize the likelihood of liquefaction rather than the potential for damage from the liquefaction.

A parameter that predicts the occurrence of damaging liquefaction for a geologic unit would greatly facilitate the preparation of liquefaction hazard maps. If the parameter could be computed from field data and incorporated into a geographic information system (GIS), it would enhance the application of this technology to the preparation of hazard maps. An example of such a parameter is the liquefaction potential index, which originally was proposed and applied in Japan by Iwasaki et al. (1978). Although the parameter has not been extensively evaluated other than in one

study in Japan, the capability of the liquefaction potential index (LPI) to describe the geographic variability of liquefaction hazard has made it an attractive candidate for application in GIS. Example applications include Frost et al. (1997), Divakarla et al. (1998), Hosseini (1998), Luna and Frost (1998), Crespellani et al. (1999), and Holzer et al. (2002).

The liquefaction potential index is evaluated here with field data collected after recent earthquakes in California. The data are cone penetration test (CPT) soundings that were conducted primarily by the U.S. Geological Survey from 1979–1996 at sites where liquefaction occurred during earthquakes. The principal purpose of the present investigation is to evaluate the index as a predictor of liquefaction occurrence, although a modest effort was made to calibrate the values of the index with the severity of liquefaction. Liquefaction occurrence as used here refers to field situations where there are surface manifestations of liquefaction such as sand boils, ground cracks, and permanent ground deformation. The prediction by the liquefaction potential index is different than that made by the simplified procedure of Seed and Idriss (1971). The simplified procedure predicts what will happen to a soil element whereas the index predicts the performance of the whole soil column and the consequences of liquefaction at the ground surface.

Liquefaction Potential Index

Iwasaki et al. (1978) developed the liquefaction potential index (LPI) to predict the potential of liquefaction to cause foundation damage at a site. They assumed that the severity of liquefaction should be proportional to the

1. Thickness of the liquefied layer;
2. Proximity of the liquefied layer to the surface; and
3. Amount by which the factor safety (FS) is less than 1.0, where FS is the ratio of the liquefaction resistance to the load imposed by the earthquake.

Because surface effects from liquefaction at depths greater than 20 m are rarely reported, they limited the computation of LPI to depths (z) ranging from 0 to 20 m. They proposed the following definition:

$$LPI = \int_0^{20m} Fw(z)dz \quad (1)$$

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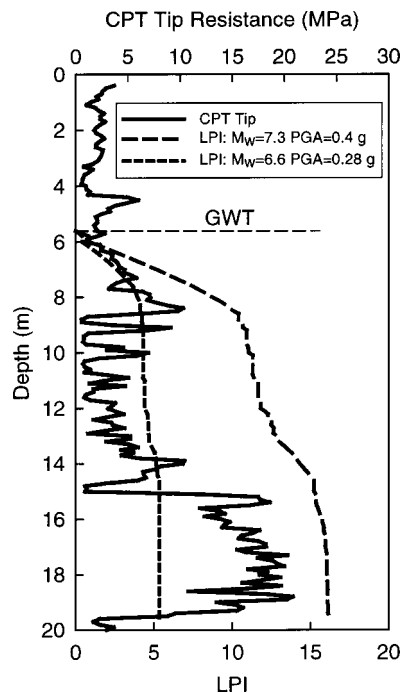


Fig. 1. Example calculation of LPI with a CPT sounding for two earthquakes: An M_w 6.6 and 7.3, respectively, with peak ground accelerations (PGA) of 0.28 and 0.4 g

in which

$$F = 1 - FS \quad \text{for } FS \leq 1, \text{ and}$$

$$F = 0 \quad \text{for } FS > 1, \text{ and}$$

$$\text{Depth weighting factor, } w(z) = 10 - 0.5z$$

where z = depth in meters. By this definition, values of LPI can range from 0 for a site with no liquefaction potential to a maximum of 100 for a site where the factor of safety is zero over the entire 20-m-depth range.

Fig. 1 is an example calculation of LPI for a CPT sounding at a location subjected to two different earthquake loadings. In practice with CPT measurements, the integral in Eq. (1) is replaced with a summation of depth increments equal to the sampling interval of the CPT. To compute LPI, depth intervals with materials susceptible to liquefaction are first inferred from the CPT tip and sleeve friction. Then factors of safety against liquefaction are computed for susceptible material. In the present investigation, both identification of susceptible materials and computation of factors of safety were based on Robertson and Wride (1997). Fig. 1 shows the accumulation of LPI with depth, i.e., the partial integral of Eq. (1), for two different earthquakes: an M_w 6.6 and M_w 7.3 with peak ground accelerations of 0.28 and 0.4 g, respectively. Note that the M_w 7.3 earthquake produces an LPI of 16, the value at 20 m, which is substantially larger than the LPI of about 5 produced by the M_w 6.6 earthquake. The example also illustrates how the contribution to LPI may vary significantly with depth. In the example, most of the LPI contribution is from the sandy interval between 6 and 9 m.

LPI has not been widely applied in field investigations primarily because of both the limited evaluations and calibrations of the LPI scale and the need for detailed information on the thickness of susceptible layers and their liquefaction resistance. Iwasaki et al. (1982) conducted the most thorough effort to calibrate the

significance of numerical values of LPI. They evaluated LPI at 85 sites in Japan for six earthquakes. Of the 85 sites, 63 showed evidence of liquefaction and 22 did not. It is unclear from their publication whether “site” refers to a single standard penetration test (SPT) boring or is an average of multiple borings within an area, but it appears they were using individual borings. Their calculated LPI values were based on SPT blow counts, which typically are measured at a 1-m spacing in Japan. They concluded that severe liquefaction is likely at sites with $LPI > 15$ and is not likely at sites with $LPI < 5$. Other attempts to relate LPI values to liquefaction severity are more modest. Chameau et al. (1991) conducted cone penetration testing at six sites underlain by artificial fill that liquefied during the 1989 Loma Prieta, Calif., earthquake. They concluded that LPI captured the relative risk of the six sites. Luna and Frost (1998) used LPI to map variations of liquefaction potential on Treasure Island, a hydraulic fill in San Francisco Bay, Calif., and compared the values to damage.

Methodology and Data

In the present investigation, penetration data from CPT soundings were relied upon both to identify susceptible materials and to compute factors of safety. CPT provides greater resolution and characterization of layering at a site and is potentially a more rigorous tool for determining LPI at a site than is SPT. Despite the reliance on CPT, most of the CPT soundings in this investigation have nearby SPT soundings that generally confirm the CPT-based identification of susceptible layers and their factors of safety. The SPT sampling, however, is insufficient to support an independent investigation of LPI based on SPT N values.

Factors of safety against liquefaction were computed with the simplified procedure originally proposed by Seed and Idriss (1971) as modified and adapted to the CPT by Robertson and Wride (1997). Factors of safety were computed at 10-cm depth intervals, corresponding to the digitization of the USGS CPT soundings. In the simplified procedure, the factor of safety is computed by dividing the liquefaction cyclic resistance ratio, which is determined from the penetration resistance, by the cyclic shear ratio produced by the earthquake. Different earthquake magnitudes were accommodated in this investigation by using the magnitude scaling factors developed by Idriss (Youd and Idriss 1997).

The CPT soundings used here primarily are from a large database that was amassed and published by the USGS over the past two decades (see references in Table 1). Since 1979, the USGS has systematically mapped liquefaction effects and conducted significant subsurface investigations, including both CPT and SPT, at liquefaction sites following domestic earthquakes. For these investigations, CPT soundings typically were conducted for general exploration and then specific layers were sampled by SPT. The data considered here are from sites underlain by natural soils. Soundings were conducted at sites shaken by five earthquakes with M_w ranging from 6.5 to 6.9 (Table 1). The typical approach by the USGS following most earthquakes was to select a few ground failure sites for detailed subsurface investigation. However, following the M_w 6.9 1989 Loma Prieta, Calif., earthquake, a comprehensive regional investigation of multiple sites, including sites without liquefaction, was conducted.

The results presented here are based on 243 CPT soundings that were performed at 27 sites, where the term site indicates a location of concentrated field investigation. As used here, a site may include areas both with and without liquefaction. Sites were

Table 1. Postearthquake Investigations Included in this Study

Earthquake	Year	M_w	References
Imperial Valley	1979	6.5	Bennett et al. 1981; Youd and Wieczorek, 1982
Loma Prieta	1989	6.9	Bennett and Tinsley 1995; Boulanger et al. 1997; Holzer 1998
San Fernando	1971	6.6	Bennett 1989
Superstition Hills	1987	6.6	Bennett et al. 1981; Holzer et al. 1989
Northridge	1994	6.7	Bennett et al. 1998; Holzer et al. 1999

located in three regions in California: (1) the Monterey bay region, which was shaken strongly by the 1989 Loma Prieta earthquake; (2) the Imperial Valley, which was shaken by the 1979 Imperial Valley and 1987 Superstition Hills earthquakes; and (3) the San Fernando Valley, which was shaken by the 1971 San Fernando Valley and 1994 Northridge earthquakes. The number of soundings in each region, respectively, is 158, 52, and 33. For each CPT sounding, a LPI value was computed for all earthquakes in the region. By noting whether or not liquefaction occurred near the sounding, each LPI value was classified as being in either a “liquefied” or “nonliquefied” area. In most cases, the liquefied area included either lateral spreading or ground cracking. Of the resulting 314 LPI values that were computed, 156 and 158, respectively, were in liquefied and nonliquefied areas. Table 2 lists the number of LPI values in the liquefied and nonliquefied areas for each site along with the region, earthquake name, magnitude, and acceleration.

Note that nonliquefied LPI values resulted from one of three situations. In the first situation, no liquefaction was reported at a site. In the second situation, multiple soundings were conducted both inside and outside the liquefied areas and LPI values were designated as either liquefied or nonliquefied based on the location of the sounding. In the third situation, two earthquakes shook a site, but liquefaction only occurred during one of the earthquakes. For this situation, two LPI values could be computed for each CPT sounding in the liquefied area with one value classified as liquefied (for the stronger earthquake) and the other as nonliquefied. The large lateral spread that intersected Balboa Boulevard in the San Fernando Valley during the 1994 Northridge earthquake provides an example of the latter two situations (Holzer and others 1999). Subsurface exploration of the 1994 lateral spread extended outside the zone of failure. This permitted some LPI values to be classified as nonliquefied for the 1994 earthquake. However, no ground deformation at Balboa Boulevard was reported during the 1971 San Fernando earthquake. This permitted LPI values for the 1971 earthquake, which were computed from the same soundings as those used for the 1994 earthquake, to be all classified as nonliquefied.

Prediction of Liquefaction Occurrence

Histograms and cumulative percentages of LPI values for soundings in both liquefied and nonliquefied areas are shown in Fig. 2. Fig. 2(a) is the histogram for all 314 LPI values and Figs. 2(b–d), respectively, are histograms for the Monterey Bay region and the Imperial and San Fernando Valleys. The histograms indicate that in general liquefaction occurrence is associated with higher LPI values and nonliquefaction is associated with lower values, although LPI does not cleanly discriminate between liquefied and nonliquefied areas. For all of the data [Fig. 2(a)], the cumulative percentage curve for LPI values in liquefied areas indicates that LPI is approximately linearly distributed between values of 0 and

15. By contrast, about 65% of the LPI values in nonliquefied areas are less than one. Comparison of the histograms and cumulative percentages from the three regions also show variability between regions. The Monterey Bay region [Fig. 2(b)] has higher LPI values in nonliquefied areas than does the Imperial Valley [Fig. 2(c)]. The San Fernando Valley has the smallest range of LPI values [Fig. 2(d)].

The trends observed in the histograms and cumulative percentages in Fig. 2 suggest that the index is useful as a screening tool to predict liquefaction occurrence, particularly in regional studies involving liquefaction hazard mapping. However, assessment of the LPI index in a probabilistic framework should provide more insight into both the reliability of the index as a predictor of liquefaction and as a tool for risk-based liquefaction potential evaluation. To compute the probability of liquefaction occurrence, the number of LPI values in liquefied areas in each LPI increment, e.g., from $LPI > 9$ to $LPI \leq 10$, was divided by the total number of LPI values in the increment for both liquefied and nonliquefied areas. These values were then regressed with a hyperbolic function. Fig. 3 shows the probability of liquefaction as a function of LPI for all of the individual soundings [Fig. 3(a)] as well as for the Monterey Bay region [Fig. 3(b)], Imperial Valley [Fig. 3(c)], and San Fernando Valley [Fig. 3(d)].

Fig. 3(a), which is the probability computed from all 314 LPI values, indicates that the likelihood of liquefaction occurrence increases as LPI increases. Probability of liquefaction exceeds 48 and 94%, respectively, where LPI equals or exceeds 2 and 15. The probability distributions of the three study regions differ, however. The probability of liquefaction is higher at lower values of LPI for both the Imperial Valley [Fig. 3(c)] and San Fernando Valley [Fig. 3(d)] regions than it is for the Monterey Bay region [Fig. 3(b)].

Differences in geologic settings, depth to ground water, and criteria for selecting study sites in each region most likely caused the differences in probability distributions between regions. Both the thickness and cleanliness of sand bodies in a region are determined by the geologic setting of region; a region with thick sand layers would be expected to have higher LPI values than one with thin layers. Many sites in the Monterey Bay region are underlain by thick and extensive sand bodies, which were deposited during large river floods. By contrast, sites in the San Fernando Valley are underlain predominantly by alluvial fan deposits with thin liquefiable silty sand layers and relatively deep groundwater table levels. The geologic setting of the Imperial Valley is intermediate, generally consisting of sites underlain by thin sand layers deposited by small rivers. Accordingly, LPI values in the Monterey Bay region would be expected to be generally higher than in the other two regions.

This impact of a geologic setting on the magnitude of LPI values can be demonstrated with histograms of LPI from two intensely explored sites in contrasting geologic settings (Fig. 4).

Table 2. List of Study Sites with Number of Soundings

Site ^a	Liquefaction ^b	Number of soundings	Earthquake		Peak ground accelerations (g)
			Name	M_w	
Juvenile Hall	Yes	5	1971 San Fernando	6.6	0.5
Heber Road	Yes	11	1979 Imperial Valley	6.5	0.5
McKim	Yes	8	1979 Imperial Valley	6.5	0.51
Radio Tower	Yes	2	1979 Imperial Valley	6.5	0.22
River Park	Yes	14	1979 Imperial Valley	6.5	0.22
Wildlife	Yes	8	1987 Superstition Hills	6.6	0.21
AIR	Yes	4	1989 Loma Prieta	6.9	0.26
CMF&FAR	Yes	15	1989 Loma Prieta	6.9	0.36
GRA	Yes	4	1989 Loma Prieta	6.9	0.34
JEF	Yes	17	1989 Loma Prieta	6.9	0.21
KET	Yes	2	1989 Loma Prieta	6.9	0.47
LEN	Yes	4	1989 Loma Prieta	6.9	0.22
ML	Yes	19	1989 Loma Prieta	6.9	0.28
MRR	Yes	1	1989 Loma Prieta	6.9	0.4
PD	Yes	1	1989 Loma Prieta	6.9	0.22
RAD	Yes	2	1989 Loma Prieta	6.9	0.38
SCA	Yes	6	1989 Loma Prieta	6.9	0.23
SEA	Yes	2	1989 Loma Prieta	6.9	0.22
SIL	Yes	4	1989 Loma Prieta	6.9	0.38
SPR	Yes	4	1989 Loma Prieta	6.9	0.33
TAN	Yes	1	1989 Loma Prieta	6.9	0.13
Balboa Blvd.	Yes	13	1994 Northridge	6.7	0.84
Wynne Ave.	Yes	14	1994 Northridge	6.7	0.51
Balboa Blvd.	No	13	1971 San Fernando	6.6	0.45
Juvenile Hall	No	1	1971 San Fernando	6.6	0.5
Wynne Ave.	No	14	1971 San Fernando	6.6	0.25
Heber Road	No	2	1979 Imperial Valley	6.5	0.5
Radio Tower	No	2	1979 Imperial Valley	6.5	0.22
Vail Canal	No	5	1979 Imperial Valley	6.5	0.14
Heber Road	No	13	1987 Superstition Hills	6.6	0.1
Mc-Kim	No	8	1987 Superstition Hills	6.6	0.2
Radio Tower	No	4	1987 Superstition Hills	6.6	0.15
River Park	No	14	1987 Superstition Hills	6.6	0.15
Vail Canal	No	5	1987 Superstition Hills	6.6	0.21
AIR	No	4	1989 Loma Prieta	6.9	0.26
CMF&FAR	No	10	1989 Loma Prieta	6.9	0.36
JEF	No	1	1989 Loma Prieta	6.9	0.21
KET	No	3	1989 Loma Prieta	6.9	0.47
LEN	No	2	1989 Loma Prieta	6.9	0.22
MAR	No	10	1989 Loma Prieta	6.9	0.13
MCG	No	14	1989 Loma Prieta	6.9	0.26
ML	No	5	1989 Loma Prieta	6.9	0.18
MRR	No	1	1989 Loma Prieta	6.9	0.4
PD	No	9	1989 Loma Prieta	6.9	0.17
RAD	No	3	1989 Loma Prieta	6.9	0.38
SCR	No	7	1989 Loma Prieta	6.9	0.42
SEA	No	1	1989 Loma Prieta	6.9	0.22
TAN	No	2	1989 Loma Prieta	6.9	0.13

^aSite acronyms for Loma Prieta are from Tinsley et al. (1998).

^b“Yes” indicates liquefaction observed; “No” indicates no liquefaction observed.

Fig. 4(a) is a site with thick laterally extensive sand and Fig. 4(b) is a site underlain by a deep and thin sand layer. Fig. 4(a) is based on soundings conducted along the Pajaro River near Watsonville, Calif., in the Monterey Bay region. Liquefaction and lateral spreading occurred during the 1989 Loma Prieta earthquake in a 6-m-thick sandy floodplain deposit that fills a former 400-m-wide

river channel (Holzer et al. 1994). An LPI value of 7 or greater generally distinguishes areas where surface manifestations of liquefaction were observed from areas where it was not observed. The minimum observed LPI in the liquefied area is about seven. The LPI values of all but one sounding, (CMF)-11, in the non-liquefied area are less than six. CMF-11, which has an LPI

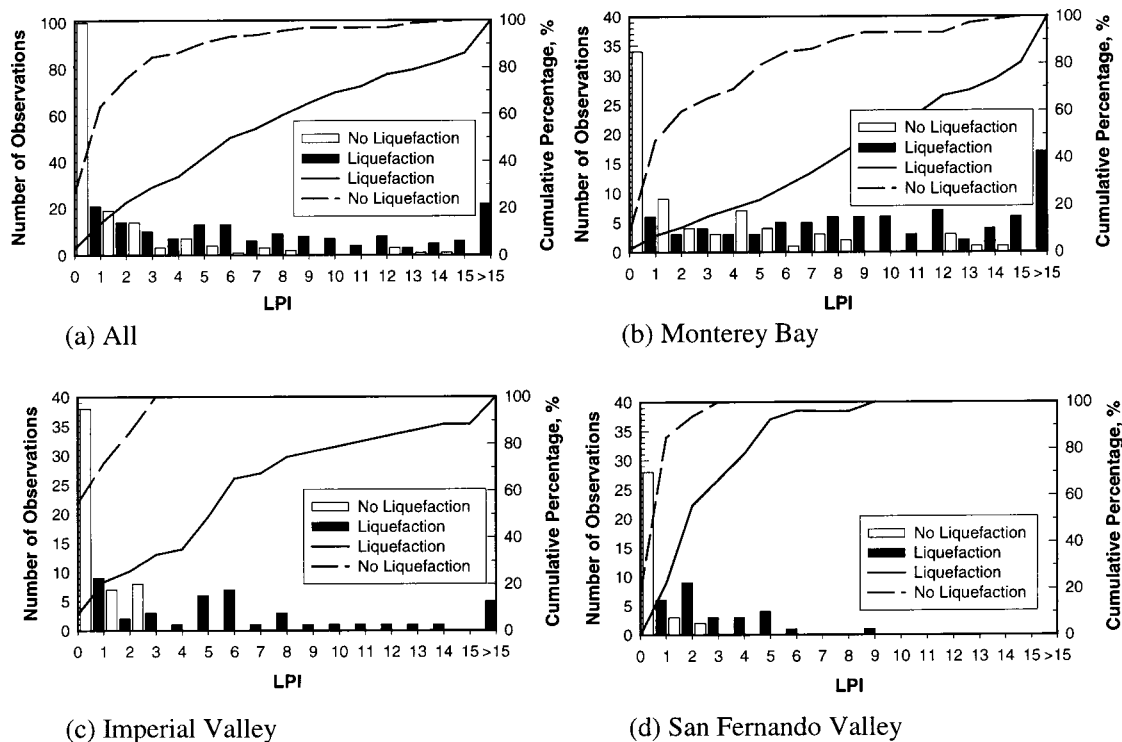


Fig. 2. Histograms and cumulative percentages of LPI values for individual soundings in areas with and without liquefaction in historic California earthquakes: (a) all regions; (b) Monterey Bay region; (c) Imperial Valley region; and (d) San Fernando Valley region

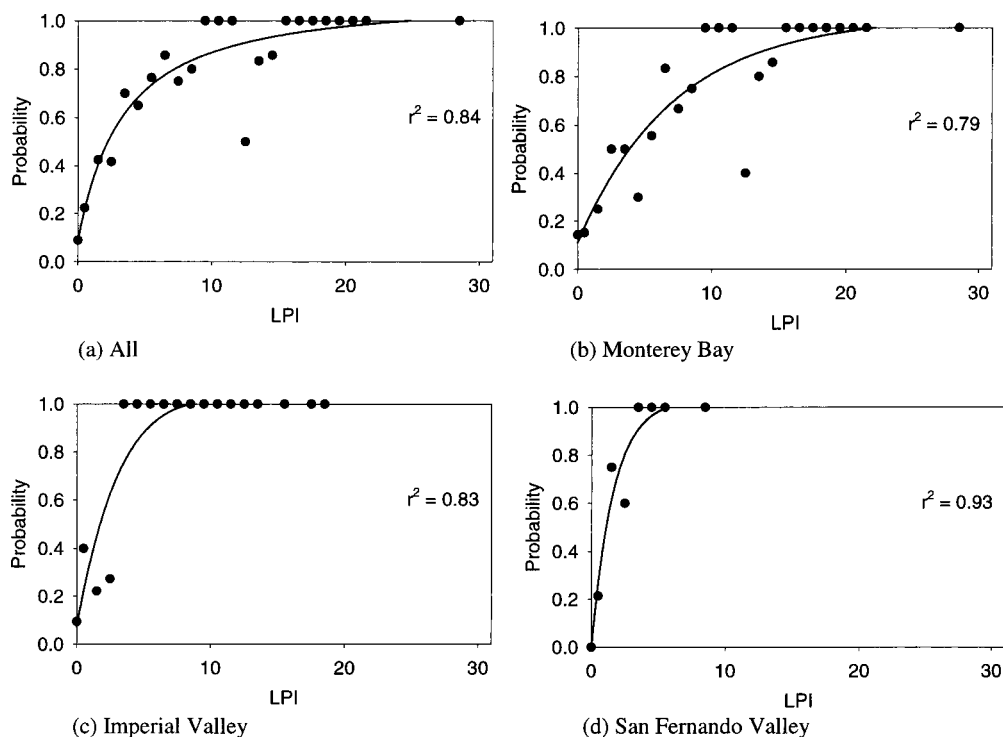


Fig. 3. Probability of liquefaction occurrence based on LPI: (a) all regions; (b) Monterey Bay region; (c) Imperial Valley region; and (d) San Fernando Valley region

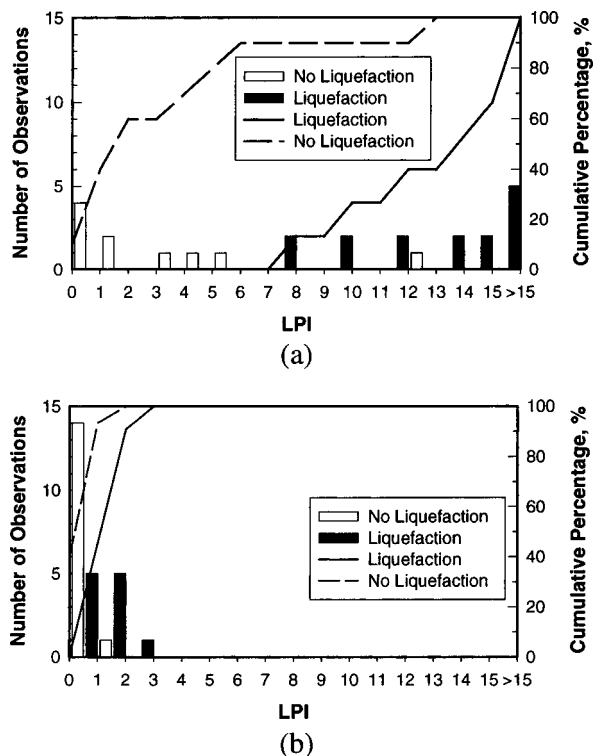


Fig. 4. Histograms and cumulative percentages of LPI for soundings at two sites with liquefaction in historic California earthquakes: (a) Miller and Farris farms, Monterey Bay region; and (b) Balboa Boulevard, San Fernando Valley

= 12.8 (Table 3), penetrated a significant interval of susceptible sand. The sand layer at CMF-11, however, is not widespread; adjacent soundings only penetrated fine-grained material. Thus, if liquefaction did indeed occur at CMF-11, it was not laterally extensive. Fig. 4(b) is based on soundings in the alluvial fan deposit that underlies the San Fernando Valley. The soundings were performed at a location, Balboa Boulevard, where the 1994 Northridge earthquake induced liquefaction and caused a 0.5-km-wide lateral spread. The liquefied layer was less than 3 m thick and ranged in depth from 7.2 to 10.7 m (Holzer et al. 1999). Ground deformation was not reported at this site during the 1971 San Fernando earthquake. The maximum LPI predicted for the

liquefied area caused by the Northridge earthquake is only 2.3 (Table 4). While five of the LPI values for the liquefied area are equal to or less than 1.0, five of the LPI values are between 1 and 2. Fourteen of 15 LPI values for the nonliquefied condition are equal to or less than 0.5, and the other one is 1.1. The average LPI for the liquefied and nonliquefied areas, respectively, are 1.2 and 0.3.

While differences in the magnitude of LPI values between regions are probably caused by contrasting geologic settings, the high probabilities of liquefaction occurrence predicted at low-LPI values for the Imperial and San Fernando Valleys as well as the high coefficients of determination (r^2) most likely are a consequence of the manner in which sites were selected for investigation. Subsurface investigations in the Imperial and San Fernando Valleys were conducted at sites where liquefaction was observed. By restricting field investigations only to sites with liquefaction, sampling of nonliquefied areas was limited. This selective sampling of sites with liquefaction should increase the probability of liquefaction occurrence. In other words, if investigation sites in these two regions had been randomly selected, more LPI values from nonliquefied areas would have been included and the probability of liquefaction occurrence for specific LPI values would be lower. By contrast, the investigation in the Monterey Bay region was regional in scope and included numerous sites at which liquefaction was not observed in the 1989 earthquake. If this reasoning is correct, the probability distribution from the Loma Prieta earthquake region [Fig. 3(b)] provides a more reliable LPI-based prediction of the probability of liquefaction occurrence. Its lower r^2 reflects the natural variability introduced by the inclusion of more nonliquefied study areas.

Prediction of Liquefaction Severity

In the present investigation, the ability of LPI to discriminate between liquefied and nonliquefied areas was of primary interest. The utilization of LPI in engineering practice and seismic hazard mapping would be greatly enhanced, however, if LPI also could be correlated with damage from liquefaction, i.e., its severity. This was the original purpose of LPI as proposed by Iwasaki et al. (1978).

Many of the soundings conducted in the Monterey Bay region after the Loma Prieta earthquake were within areas of detailed mapping of ground performance that permit correlation of LPI

Table 3. Cone Penetration Test Soundings and Liquefaction Potential Index Values for Miller and Farris Farms, Monterey Bay Region

Sounding ^a	Liquefaction	Liquefaction potential index	Sounding	Liquefaction	Liquefaction potential index
CMF3	Yes	11.8	FAR60	Yes	14.6
CMF4	Yes	13.5	FAR61	Yes	13.1
CMF5	Yes	17.9	CMF1	No	1.1
CMF6	Yes	22	CMF2	No	3.4
CMF7	Yes	11.2	CMF10	No	5.1
CMF8	Yes	16.1	CMF11	No	12.8
CMF9	Yes	21.4	CMF12	No	1.5
CMF49	Yes	14.1	CMF13	No	0.3
CMF50	Yes	16.1	FAR55	No	0
FAR56	Yes	7.6	FAR62	No	0.3
FAR57	Yes	9.3	FAR63	No	4.5
FAR58	Yes	7.8	FAR64	No	0.2
FAR59	Yes	10			

^aSounding acronyms from Bennett and Tinsley (1995).

Table 4. Cone Penetration Test Soundings and Liquefaction Potential Index Values for Balboa Boulevard, San Fernando Valley Region

Sounding ^a	1994 Northridge		1971 San Fernando	
	Liquefaction	Liquefaction potential index	Liquefaction	Liquefaction potential index
Balboa-2	No	0	No	0
Balboa-3	Yes	1.3	No	0.3
Balboa-4	Yes	0.2	No	0
Balboa-5	Yes	1	No	0.4
Balboa-6	Yes	0.7	No	0.3
Balboa-7	Yes	2.3	No	1.1
Balboa-8	Yes	1.5	No	0
Balboa-10	Yes	1.7	No	0.2
Balboa-11	Yes	0.2	No	0
Balboa-12	Yes	0.9	No	0.4
Balboa-13	Yes	1.9	No	0.5
Balboa-13.5	Yes	1.6	No	0.4
Balboa-15	No	0.1	No	0

^aSounding acronyms from Bennett et al. (1998).

with ground performance. For 50 soundings at 20 sites previously reported by Toprak et al. (1999), the nature of ground deformation near each sounding was carefully noted. For these soundings, ground performance was divided into four categories ranging in decreasing severity from lateral spreads, to ground cracking and sand boils, to sand boils, to no ground disturbance. The correlation (Fig. 5) indicates that LPI decreases from a median of 12 for soundings in lateral spreads to 0 for soundings where no surface effects were reported. The results are consistent with the classification by Iwasaki et al. (1982), who proposed that an LPI of 15 and <5, respectively, corresponded to sites with severe liquefaction and only minor damage.

Discussion

This investigation indicates that LPI provides a useful tool for risk-based decisions for liquefaction hazard mapping. Distributions of LPI from postearthquake case histories of liquefaction enable probabilistic estimates of liquefaction given specific values of LPI. LPI data from the Monterey Bay region indicate that a location with an LPI value of 15 has a probability of 93% of showing surface manifestations of liquefaction; a location with an LPI value of 5 has a probability of 58%. To improve these probability distributions, field data from future case histories must be free from sampling bias. Field emphasis during postearthquake investigations at sites with liquefaction may produce misleadingly high probabilities of liquefaction. This problem is similar to the potential bias in probabilistic treatments of the simplified procedure created by inadequate sampling of sites without liquefaction (Liao et al. 1988). Fortunately, the postearthquake investigation in the Monterey Bay region included a large number of sites without indications of liquefaction. Accordingly, the regression for that region, Fig. 3(b), provides the least biased estimate of the probability of liquefaction occurrence.

Although the present investigation emphasized predicting the occurrence of liquefaction, LPI would be of greater practical use if it indicated the severity of liquefaction and particularly damage. A correlation of LPI values with the severity of surface effects for the Monterey Bay region during the Loma Prieta earthquake is

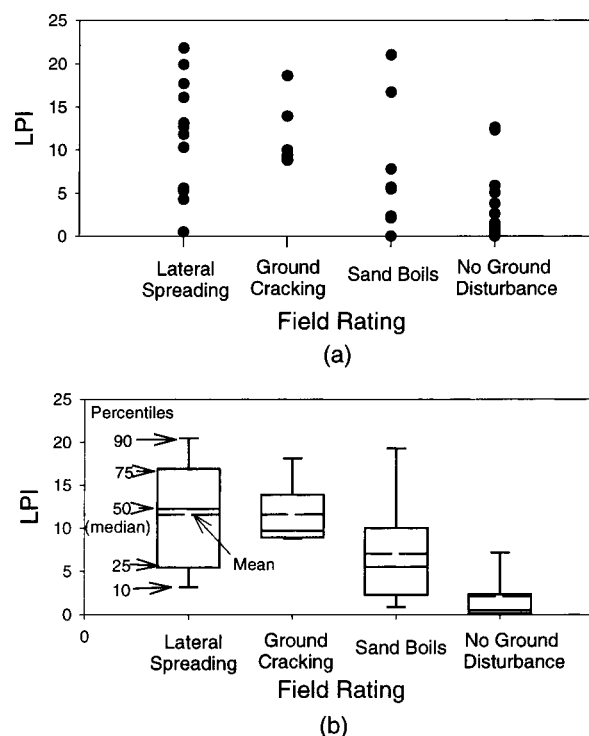


Fig. 5. Correlation of LPI values with surface effects for the 1989 Loma Prieta Earthquake: (a) LPI values and (b) percentiles

consistent with the severity scale proposed by Iwasaki et al. (1982) which indicated liquefaction was likely to be severe where $LPI > 15$ and not likely at $LPI < 5$. In the Monterey Bay region, sand boils appeared at $LPI \geq 5$ and lateral spreading was observed where $LPI \geq 12$. The agreement in trends between the LPI values based on CPT soundings at historic liquefaction sites in California and LPI values based on SPT soundings at Japanese liquefaction sites by Iwasaki et al. (1982) is encouraging. New data from the recent earthquakes such as 1999 Turkey and Taiwan earthquakes should provide additional data to relate LPI with liquefaction severity.

Finally, uncertainty in the predictive capability of LPI can be expected to be inherent when it is applied to natural systems. Natural geologic systems in general are heterogeneous and it is easy to visualize field settings that would introduce uncertainty into correlations of LPI with liquefaction occurrence. For example, if liquefaction at a site were limited to isolated pockets that were not laterally continuous, surface manifestations of liquefaction might not occur yet LPI values might be significant. Conversely, a thin, deeply buried liquefied layer that is geographically widespread might be conducive to ground failure and lateral spreading despite low values of LPI. This natural variability may be the explanation of the absence of a clean separation between liquefaction and nonliquefaction data in the histograms in Fig. 2.

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